Research Note

Are Crab-type Supernova Remnants (Plerions) Short-lived?

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Summary. Arguments are given for a possible picture of the origin, maintenance, and lifetimes of the so-called Crab-like supernova remnants. It is suggested that these objects imply the existence of at least two distinct types of supernova events. A possible connection of the remnant types with the optically defined supernovae of Type I and Type II is discussed. Accepting that a pulsar is formed in at least some supernova events, the proposal is made that a rapidly rotating, rapidly slowing pulsar is necessary to create and maintain a Crab-like supernova remnant. Finally, arguments are presented that such a supernova remnant will be relatively short lived with respect to the more common shell-type of supernova remnant, perhaps surviving only 10,000–20,000 yr before fading into the Galactic background.

The name of plerion is proposed for these filled-center supernova remnants and observational possibilities for confirming their nature are suggested.

Key words: Crab Nebula — supernova remnants — pulsars

Introduction

Since it was first suggested by Weiler (1969) (see also Weiler and Seielstad, 1971 and Wilson and Weiler, 1976a) that 3C 58 represents a second object in the Galaxy which resembles the Crab Nebula in its radio properties, at least three and possibly four more radio sources have been found with similar properties (see Weiler and Shaver, 1978). With roughly a half-dozen of these unusual supernova remnants presently known and studied, some in considerable detail, it is felt that there is now sufficient information available to give a preliminary discussion of their formation, development, and lifetimes.

To summarize briefly: all supernova remnants generally show extended structure, linear polarization at least at short radio wavelengths, and a non-thermal radio spectrum usually well described by a constant spectral index. However, the “normal” or “shell-type” remnants have a shell or partial shell form, and a mean spectral index $\alpha \sim -0.45 (S \propto \nu^{-\alpha})$ (Clark and Caswell, 1976) while this new class has a filled center or blob-like form brightest in the center and decreasing in all directions toward the edges and a radio spectrum which is quite flat ($\alpha \sim -0.1 - 0.3$). These latter objects also usually exhibit a very well organized internal magnetic field structure and a high degree of linear polarization at high radio frequencies. (For a further discussion of the observational properties of these objects see Weiler and Shaver, 1978.) Because the chief characteristic of all members of the class is their filled-center form and because Crab-like is an inconvenient misnomer, we suggest the name plerion or perhaps plerion-type which we derive from the ancient Greek word plerion ($\pi\lambda\rho\nu\omicron\omicron\nu\nu\varsigma$) for full.

Discussion

In discussing the possible origin and development of plerion-type supernova remnants, we will not try to derive a fully developed theory, but merely to organize the available knowledge to give a new qualitative view of the situation. The most important astrophysical phenomena represented by the plerions would seem to be the following:

1. There are at least two types of supernovae: (a) those which form a strong shock wave propagating into the surrounding stellar envelope or the interstellar medium to produce the common shell-type supernova remnants, and (b) those which produce no or only a very weak shock wave in the supernova explosion.

2. A pulsar is formed in many, if not all, supernova explosions.

3. In some supernova explosions—preferentially, but not exclusively, those which do not form shell-type remnants—a very fast pulsar with a high spin down rate remains after the event. This pulsar can then build and

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maintain a plerion-type of supernova remnant at the expense of its rotational energy.

4. The remnants formed in this manner are short lived and fade relatively quickly as the pulsar slows and decreases its energy loss rate.

The best evidence for point 1 is obtained by studying the remnants of historical supernovae (Clark and Stephenson, 1977b). Although there is a bias incorporated in work of this nature in the tendency to associate each possible supernova in ancient records with the remnant nearest to its position on the sky, if the 6 supernovae SN ~ 1667, Kepler’s SN 1604, Tycho’s SN 1572, SN 1181, SN 1054, and SN 1006 in the last millenium can be accepted to have produced the 6 remnants Cas A, 3C 358, 3C 10, 3C 58, 3C 144 (Crab Nebula), and PKS 1459 – 41, respectively, then the following is apparent:

a) essentially all supernovae produce a remnant of some sort.

b) of the 6 supernovae only 4 have produced a shell or partial shell type of remnant. (Neither 3C 58 nor 3C 144 show any evidence for the presence of a shell.)

c) the type of remnant formed seems to be relatively independent of the properties of the surrounding interstellar medium and is probably a consequence of the explosion itself. (3C 358 at 1200 pc from the Galactic plane and PKS 1459 – 41 at 600 pc from the plane are shell type remnants as is 3C 10 only 150 pc from the plane while 3C 58 in the outer regions of the Galaxy and 430 pc from the plane does not form a shell nor does 3C 144 at only 200 pc from the plane.)

Whether these two types of explosions can be directly related to the well known Types I and II supernovae defined by their optical light curves and spectra is unclear. Only two of the historical supernovae seen in our Galaxy have all well defined light curves recorded—SN 1572 and SN 1604—and both of these are Type I (Baade, 1943, 1945) and are identified with shell-type remnants. Chevalier (1977), on the other hand, has argued from the rather crude observations of SN 1054 by the ancient Chinese that its light curve is consistent with interpretation as a Type II supernova event. This supernova has then left the plerion-type remnant, the Crab Nebula. Although such small numbers cannot be interpreted with certainty, an indication clearly exists that shell-type supernova remnants are more likely to be formed from Type I events while plerion-type remnants are more closely related to Type II explosions.

The evidence for point 2—that at least one pulsar must be formed in most if not all supernova events—is inferred solely from pulsar studies. The causal relationship between supernovae and pulsars is shown by the Crab Nebula and Vela X supernova remnant-pulsar associations and the rough statistical equivalence between supernova rates for our Galaxy inferred from extragalactic supernovae (Tammann, 1974) and pulsar birth rates is discussed by Taylor and Manchester (1977). However, as long as some supernovae can cause the formation of pulsars, the exact numerical relation between them is not critical to our argument here.

Point 3 rests, unfortunately, entirely on our knowledge of the Crab Nebula. There the presence of a pulsar is known, and the pulsar is acknowledged to be maintaining the present extended radio nebula and probably caused its formation. What is not generally emphasized is the uniqueness of this pulsar. It has the highest rotation rate and the largest slow down rate of any pulsar known and is thus expending its rotational energy much more rapidly than any other known pulsar. Presumably this energy loss, through conversion processes not yet well understood, is used to maintain the surrounding nebula known as the Crab.

The rotational energy loss rate \( \Delta T \) of a pulsar is

\[
\Delta T \propto \frac{I \dot{P}}{P^3}
\]

where \( I \) is the moment of inertia of the pulsar and \( \dot{P} \) is the rate of change of its period \( P \). Thus, to obtain a large energy loss rate the period of a pulsar should be quite short and its slow down rate quite large.

The relatively extravagant energy expenditure of the Crab pulsar (NP 0531 + 21) is shown in Table 1 where it can be compared with the two pulsars having the next two smallest rotation periods. The Crab pulsar is losing \( \sim 10^5 \) – \( 10^6 \) times more energy to its environment than either of the other two pulsars. The high energy loss rate of the Crab pulsar is also seen when it is compared to that determined from the mean properties of the presently known pulsars. The mean age of the pulsars is \( \sim 2 \times 10^6 \) yr and the mean period is \( \sim 0.6 \) (Taylor and Manchester, 1977). Using an energy calculation of the form

\[
\Delta T \propto \frac{I}{2 P^2 \tau}
\]

where \( \tau \) is the so-called characteristic age \( (P/2 \dot{P}) \), gives an energy loss rate of only \( \sim 10^{33} \) erg s\(^{-1}\) for the average pulsar—\( \sim 10^5 \) – \( 10^6 \) times smaller than that of the Crab pulsar. These much lower rotational energy loss rates for all known pulsars except NP 0531 + 21 undoubtedly explain the absence of the “Ghost Supernova Remnants” suggested by Blandford et al. (1973).

If plerions are indeed dependent on rapidly spinning, rapidly slowing pulsars as has been suggested, then they will have relatively short visible lifetimes before fading into the Galactic background (Point 4). Again, we must use the Crab pulsar as our only example at present. If it continues to slow at roughly its present rate, it will have decreased its energy loss rate to only \( \sim 1\% \) of the current value in \( \sim 9 \times 10^9 \) yr. This implies that on a time scale similar to this the pulsar will no longer be able to provide much energy to the Nebula. Because it is rapidly expanding (in fact, its expansion is accelerating!), without a continuous energy supply the Crab Nebula will...
fade due to adiabatic energy losses in only a few hundred years. Thus, as the pulsar slows the Nebula will inevitably and relatively quickly (say in \( \sim 10^4 \) yr) disappear.

A second method of estimating the lifetime of plerions is statistical and, although hampered by a very small sample, can give a rough number. From the work of Clark and Stephenson (1977b) discussed above, of the 6 supernovae observed in the last millenium in our Galaxy 4 (66\%) formed shell-type remnants and 2 (33\%) formed pleron-type remnants. This implies, albeit crudely, that roughly 1/3 of all supernovae form filled-center remnants. However, from the most recent catalogue of supernova remnants in our Galaxy by Clark and Caswell (1976) only 4 remnants (3C 58, 3C 144, G 74.9 +1.2, G 326.3 −1.8) with possibly a fifth (G 292.0 +1.8—see arguments by Lockhart et al., 1977 and Weiler and Shaver, 1978) can be readily classified as pleron-type supernova remnants. A sixth example G 21.5 −0.9 was rejected as a supernova remnant by Clark and Caswell but should be included (see Wilson and Weiler, 1976b). Thus, of 120 remnants in the Clark and Caswell catalogue, 6 or \( \sim 5\% \) are plerions. Although some plerions may be missed in supernova remnant surveys because their filled-center form and relatively flat spectral indices can cause them to be confused with Galactic H II regions, the availability of H 109\( \alpha \) measurements for most large Galactic radio sources is likely to prevent this from being a serious difficulty. This relative scarcity of plerions in catalogues of supernova remnants implies that they have much shorter lifetimes than the common shell-type remnants. If the lifetime of a shell-type supernova remnant is \( \sim 10^7 \) yr before it merges with the Galactic background radiation, then the pleron-type remnants must be visible for \( \sim 5\%, 33\% 10^6 \) or \( \sim 15000 \) yr. This age estimate agrees surprisingly well with our estimate from the active lifetime of the Crab pulsar.

The existence of a short lived class of supernova remnants has already been suggested by Clark and Stephenson (1977a) to explain the difference between the Galactic supernova rate of \( \sim 1/30 \) yr which they infer from historical records, and that \( \sim 1/150 \) yr which Clark and Caswell (1976) infer from remnant studies. Similarly, pulsar studies imply a higher supernova rate (\( \gtrsim 1/40 \) yr, Taylor and Manchester, 1977) as do counts of extragalactic supernovae (\( \gtrsim 1/25 \) yr, Tammann, 1974) than do long lived remnant statistics. Thus, the existence of a short lived class of supernova remnants in the form of pleron can provide a correction to the remnant statistics in the proper direction.

The observational verification of these suggestions, while not easy, is not beyond the limits of present technology. The most striking confirmation would be the detection of a very short period pulsar with a large slow down rate in the center of any of the plerions. In particular, finding a pulsar in 3C 58 would be useful since it is the best studied pleron after the Crab Nebula. Of the three major pulsar searches discussed by Taylor and Manchester (1977) only the Arecibo survey (Hulse and Taylor, 1974, 1975) would have detected a pulsar with a period as short as that of the Crab Nebula and their area of completeness did not include a single one of the known plerions. In addition to the problems of detecting short period pulsars, the finding of pulsars in the plerions will have other difficulties. Except for the central source of G 326.3 −1.8, all known plerions are from 2−6 times more distant than the Crab Nebula. This implies that the dispersion measures of any pulsars will be from 2−6 times greater (perhaps \( \sim 120−360 \) cm\(^{-3} \) pc) and the pulse strengths from 4−36 times weaker (perhaps \( 120−13 \) mJy mean flux density).

The detection of optical synchrotron emission from a second pleron besides the Crab Nebula would enhance the similarity between the sources. However, obscuration in most cases prevented this. Van den Bergh (1978) has been able to photograph thermal filaments near the center of 3C 58 and reports that they have similar optical morphology to those seen on a short exposure plate of the Crab Nebula. However, any optical continuum emission remains too heavily absorbed or too weak to be detected. Perhaps the expected linear polarization of any optical synchrotron emission could be used to subtract the sky background and obtain still deeper photographs.

Finally, a detection in the X-ray region of an X-ray pulsar or of an X-ray source with a non-thermal spectrum would support the hypothesis of an active source of energy remaining in the plerions. The radiative lifetimes of synchrotron electrons emitting in the X-ray region are so short that they must be continuously replenished. Simple scaling of the Crab Nebula’s properties with distance suggests that the other plerions may have from 1/4−1/40 of its X-ray flux density. Detection of such levels should be possible with instruments which are currently available or which will be available in the near future.

Table 1. Rotational energy loss rates for the three fastest pulsars

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>( P ) (s)</th>
<th>( \dot{P} ) (ns/d)</th>
<th>Energy loss rate ( (\text{erg s}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab 0531+21</td>
<td>0.033</td>
<td>36.48400</td>
<td>( 5 \times 10^{38} )</td>
</tr>
<tr>
<td>Binary 1913+16</td>
<td>0.059</td>
<td>0.000076</td>
<td>( 2 \times 10^{33} )</td>
</tr>
<tr>
<td>Vela 0833−45</td>
<td>0.089</td>
<td>10.80260</td>
<td>( 7 \times 10^{34} )</td>
</tr>
</tbody>
</table>

* The moment of inertia \( (I) \) is taken to be \( 10^{45} \text{ g cm}^2 \)

References


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Note added in proof: A more detailed discussion of Crab-like Supernova Remnants will be presented in the proceedings of the Workshop on Supernovae and Supernova Remnants (16-27 May 1978) to be published in Memorie Della Societa Astronomica Italiana.